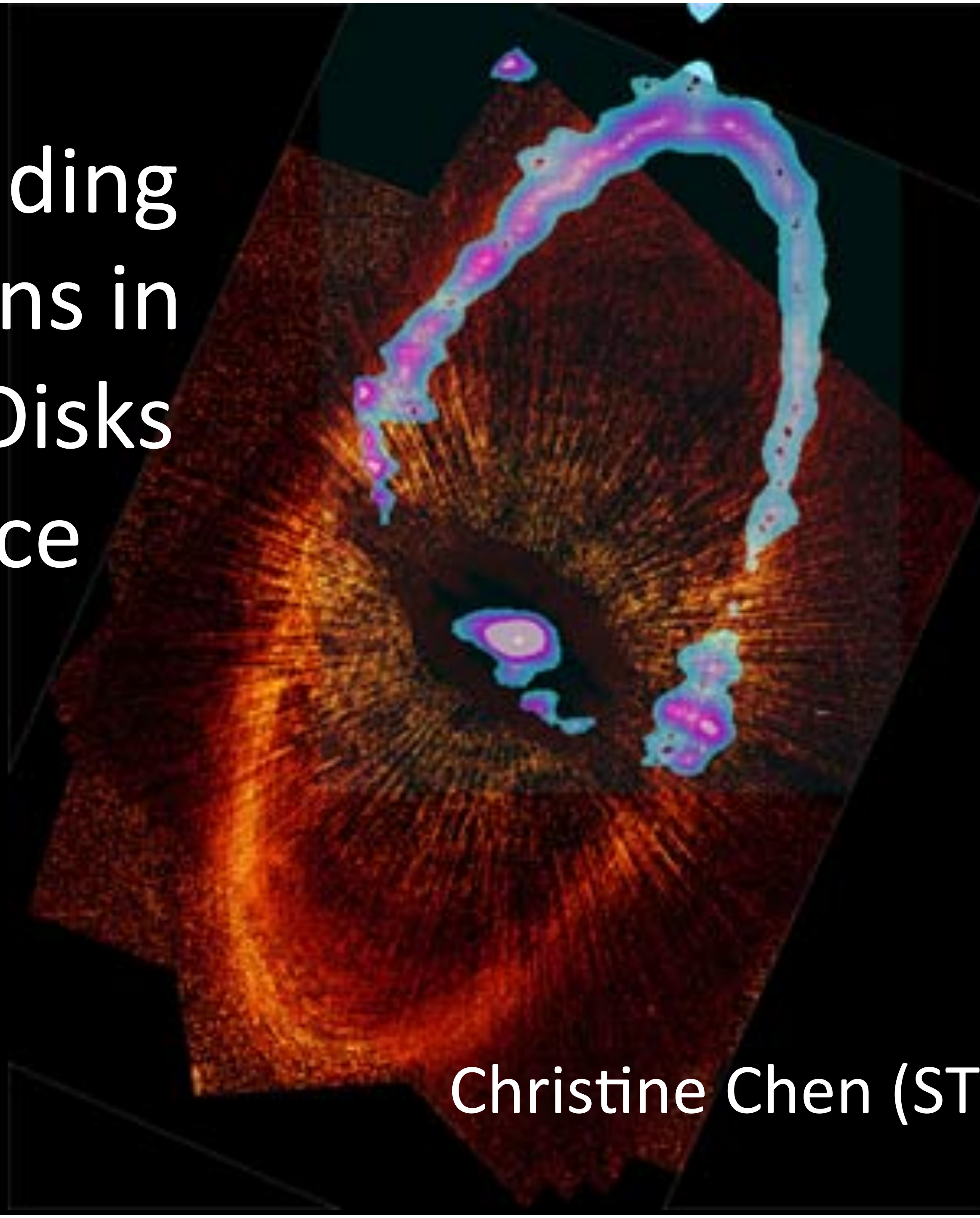
Outstanding Questions in Debris Disks Science

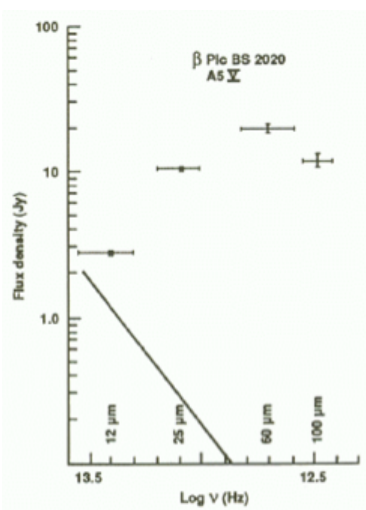


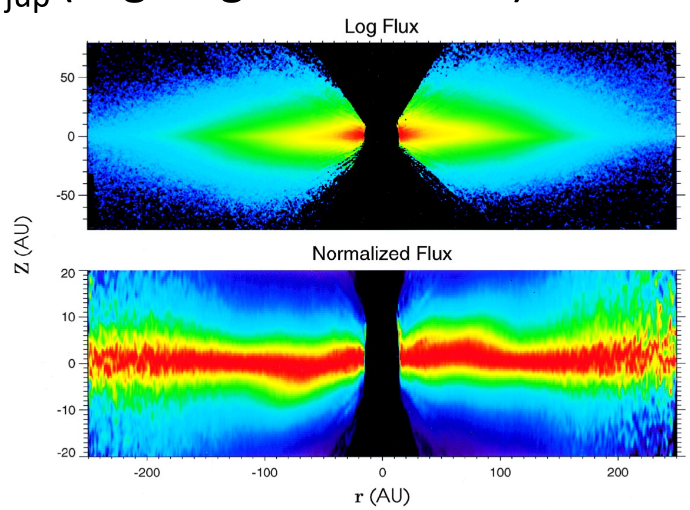
Christine Chen (STScI)

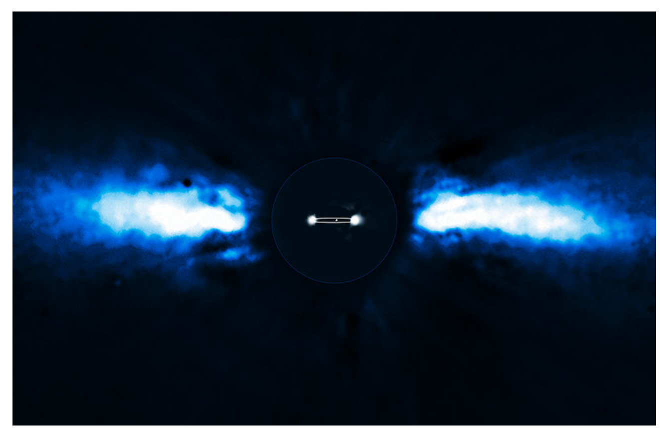
Dust in Exoplanetary Systems

A Chronology of the Discovery of the Giant Planet in the β Pic disk:

- IRAS far-infrared photometry detects thermal emission from dust that must (1) be circumstellar and (2) contain a central clearing (Sadakan & Nishida 1986; Backman & Paresce 1993)
- Initial high contrast imaging using HST/STIS discovers a warp in the inner disk that provides further support for the presence of a companion. The location of the warp is used to constrain the mass (48 – 0.17 M_{Jup})/distance (<3 AU – 150 AU) of the companion (Heap et al. 2000)
- Recent high contrast imaging using VLT/NACO images the companion at a distance of 8-13 AU and implies the presence of a planetary mass object with 9+/-3 M_{jup} (Lagrange et al. 2010)







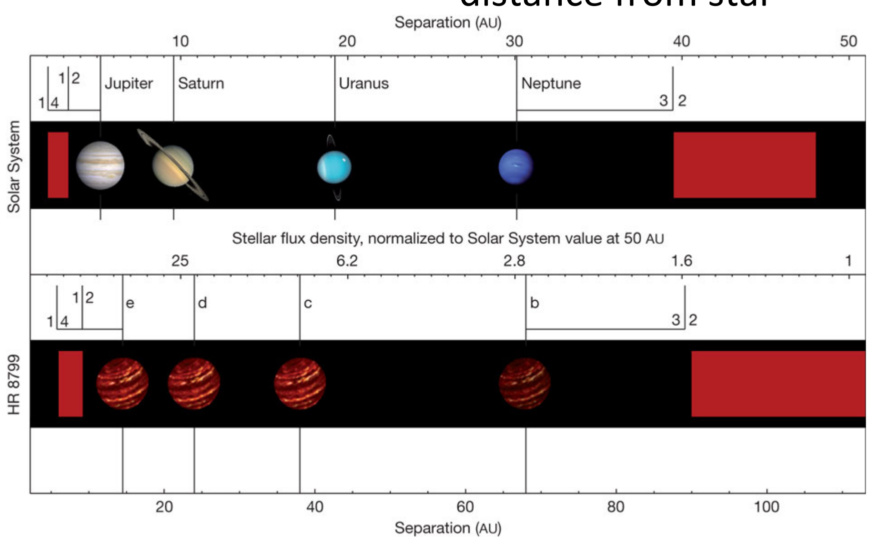
Probes of Planet Formation

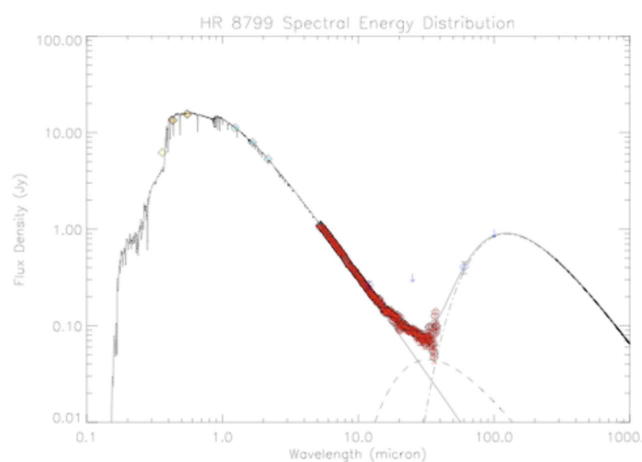
Direct Observables

- Architecture
  - Dust spatial structure
  - Central clearings, gaps, and brightness peaks may constrain the location of planets
- Composition
  - Proxy for bulk composition in minor bodies
  - Composition gradients expected based on distance from star

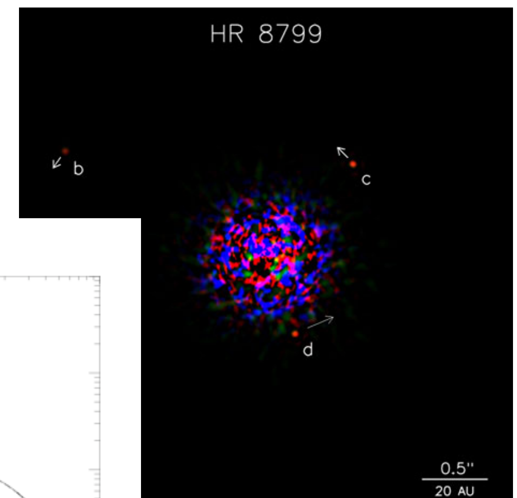
Dust Producing Epochs in Our Solar System

- Terrestrial Planet Formation
  - Oligarchic Growth
  - Giant Impacts
- Period of Late Heavy Bombardment
- Present day Zodiacal dust and dust in the Kuiper Belt



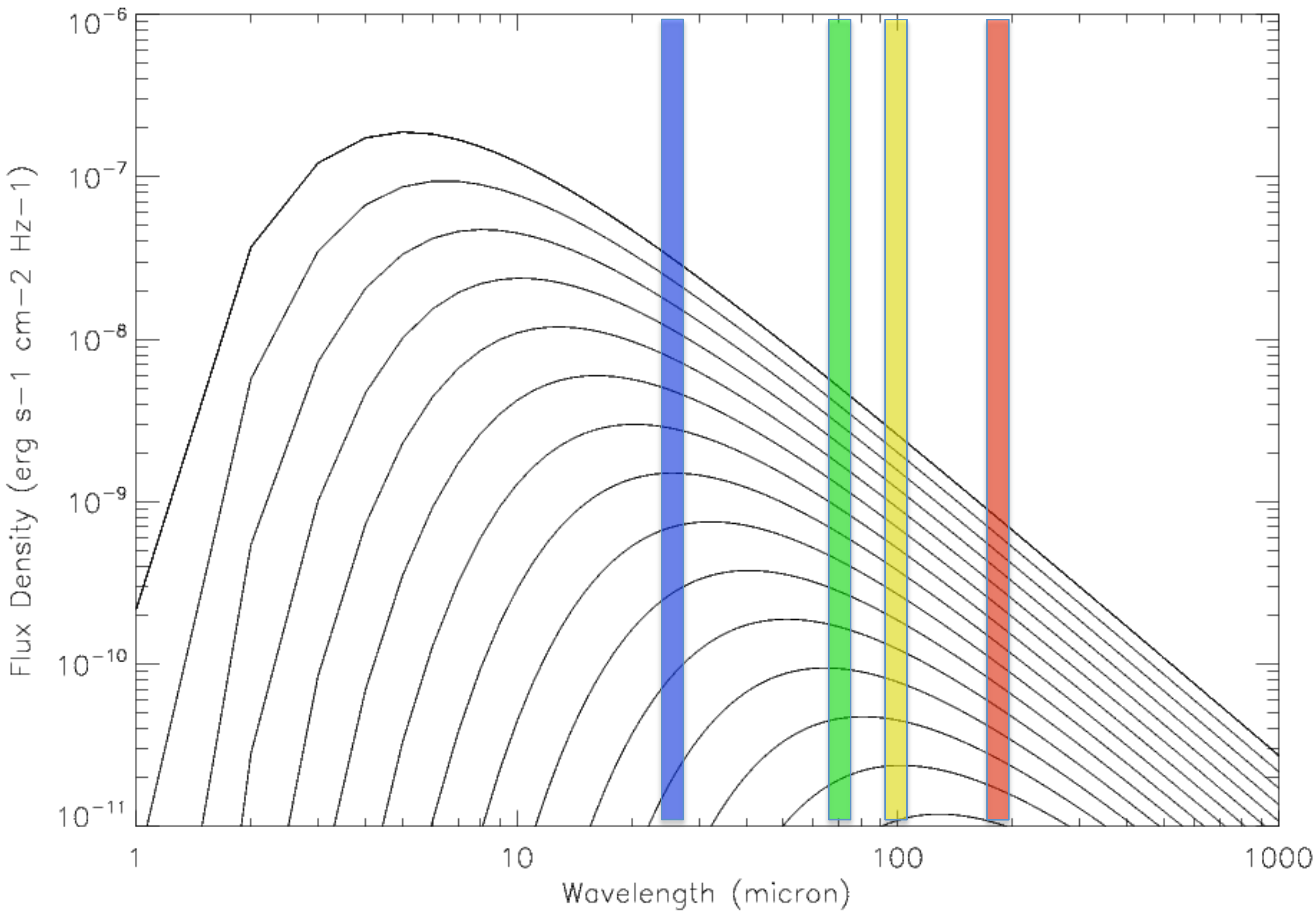


Chen et al. (2009)



Marois et al. (2008, 2012)

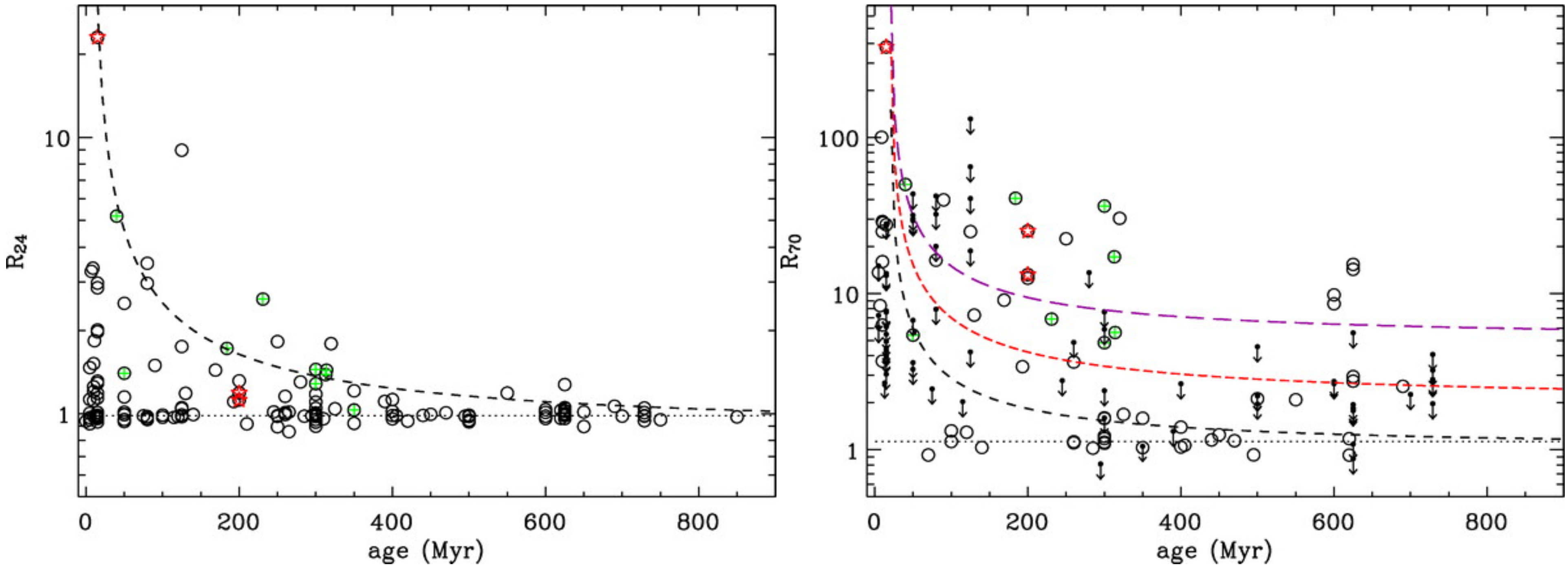
Black Body Emission



Previous Missions

- Spitzer
  - MIPS
    - Surveyed thousands of stars
    - Discovered 1000 debris disks
    - Disk fraction as a function of stellar age
      - Large variation in disk properties at a single age
      - Decline in infrared excess consistent with collisional evolution
    - Disk fraction as a function of stellar mass
    - Disk fraction as a function of presence/absence of companions
  - IRS
    - Broad SED fits giving dust distances for 500 targets
    - Spectral features observed toward 120 targets with trends
    - Detailed mineralogy for half a dozen sources
- Herschel
  - PACS
    - Surveyed hundreds of nearby stars
    - Spatially resolved half of nearby disks
    - Discovered that confusion is a bigger problem than previously thought
    - Improved debris disk fractions as a function of spectral type (decreased around A-type stars and increased around lower mass stars)
    - Discovered atomic gas toward a handful of systems
    - Characterized the silicate emission feature toward one system

Observed Debris Disk Evolution



- Infrared excess decays with time
- The shape of the upper envelope indicates that the disks are collisionally dominated
- The magnitude of infrared excess around A-type stars decays with a timescale ~150 Myr and ~400 Myr at 24 and 70 µm, respectively, consistent with inside-out evolution
- There are some very dusty disks that may be experiencing interesting evolutionary periods

(Su et al. 2006)

Observed Stellar Mass Dependence

Preliminary analysis of *Herschel* Key Program data suggests that debris disks occur more frequently around higher mass stars (Kennedy et al., in preparation):

Spectral Type	A	F	G	K	M
Frequency	26%	24%	19%	9.5%	1.3%
Stellar Luminosity	5-25 $L_\odot$	1.5-5 $L_\odot$	0.6-1.5 $L_\odot$	0.08-0.6 $L_\odot$	$<0.08\ L_\odot$
Expected 70 µm stellar photospheric flux at 50 pc	15 mJy	5 mJy	2 mJy	1 mJy	0.8 mJy

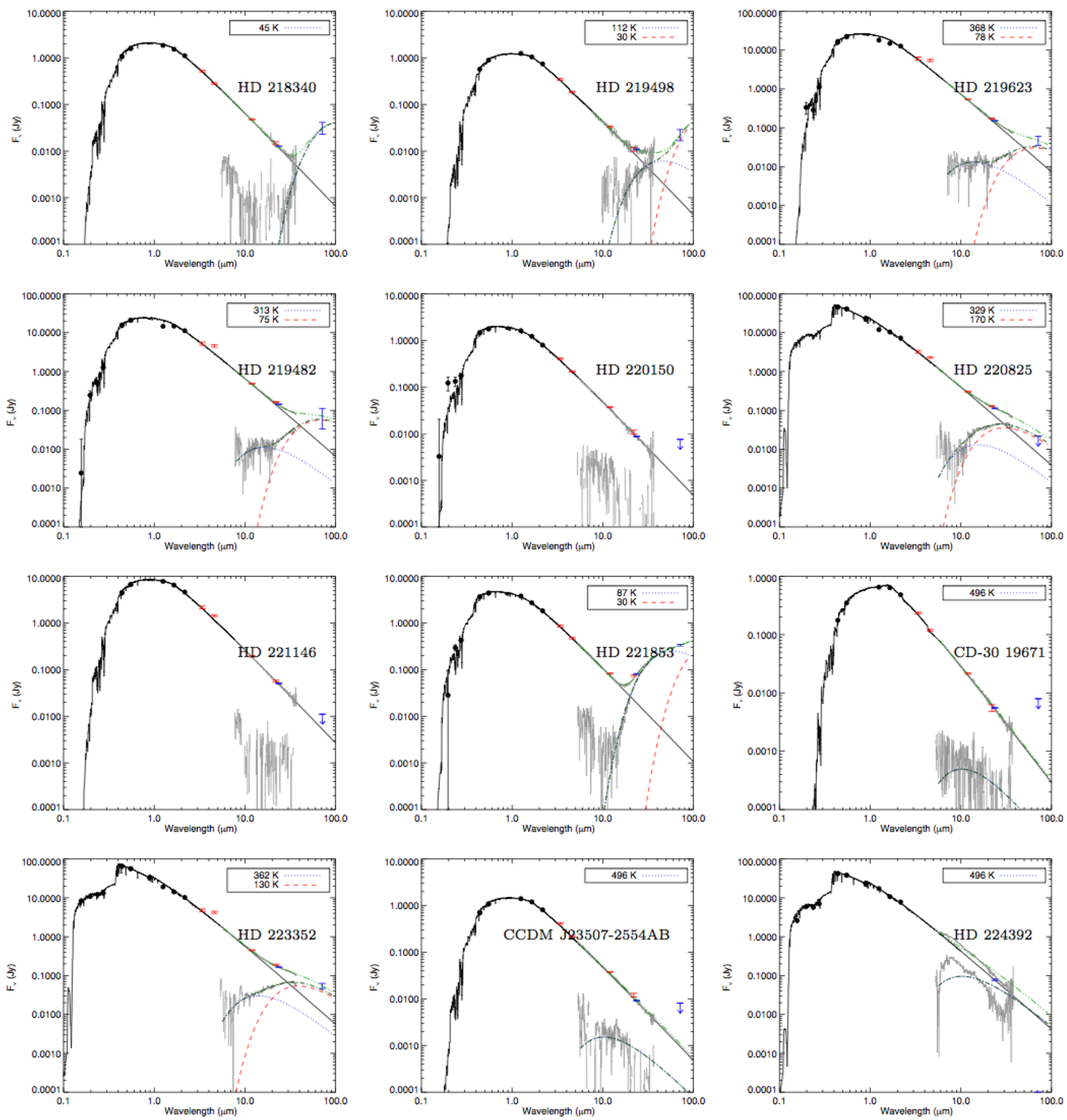
Compared with typical Far-Infrared Mission Sensitivities at 70 µm…

Spitzer had a 5σ sensitivity of 7.2 mJy in 500 s of on source integration time

Herschel had a 5σ point source sensitivity of ~3 mJy in 1 hour of observatory time

The measurements of dust frequency around late-type stars may suffer from a sensitivity bias because they possess lower luminosities than their higher mass counterparts.

Dust Spatial Distribution



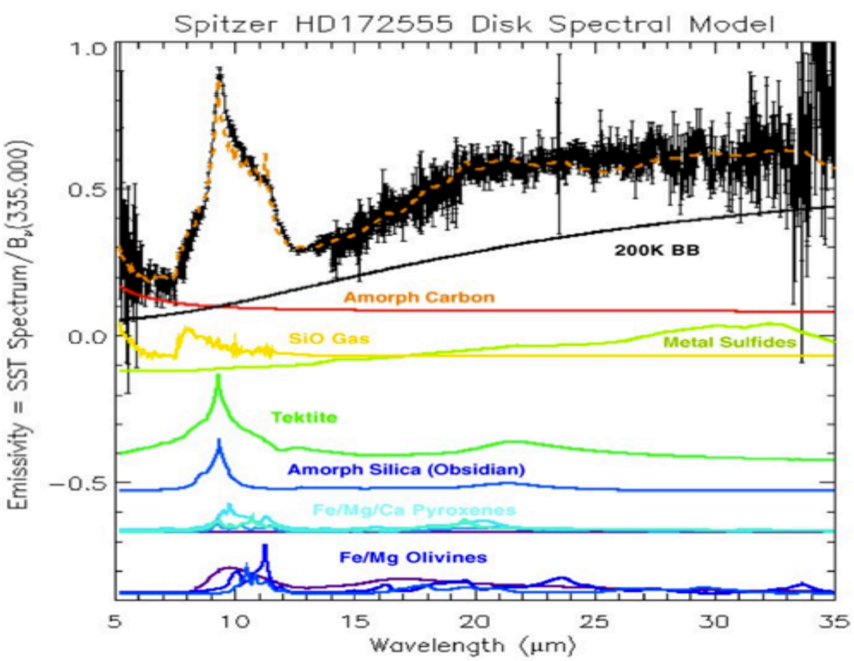
The majority of spectra lack spectral features

For the majority of systems, the Spectral Energy Distribution (SED) can be modeled assuming one, two, or three black bodies

(Chen et al. 2014)

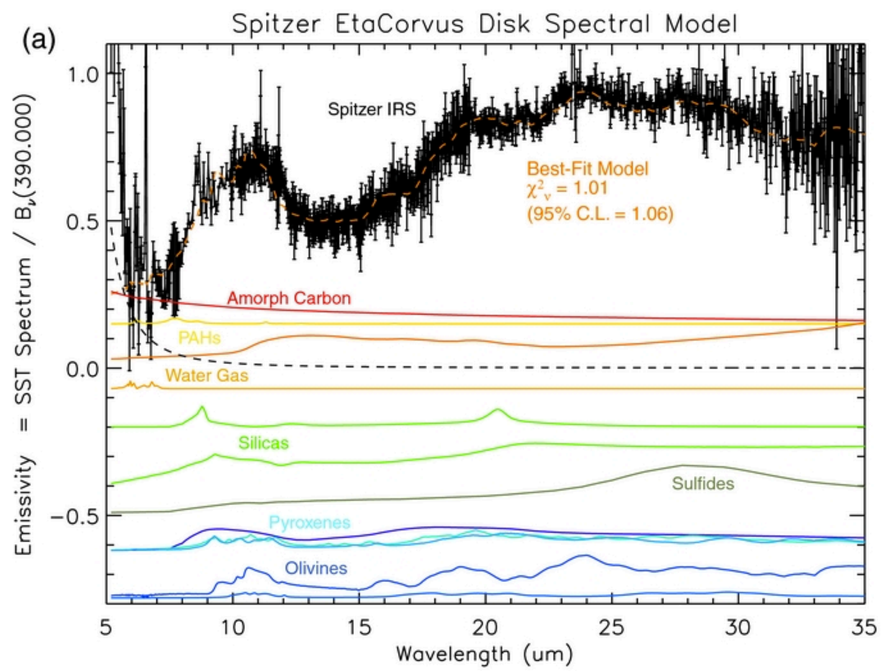
Terrestrial Temperature Dust Mineralogy

Giant Hypervelocity Collision



Glassy silicas (Obsidian and Tektite), steep grain size distribution with large quantities of fine dust and possible fundamental and first overtone emission from SiO -> Hypervelocity Collision (Lisse et al. 2009)

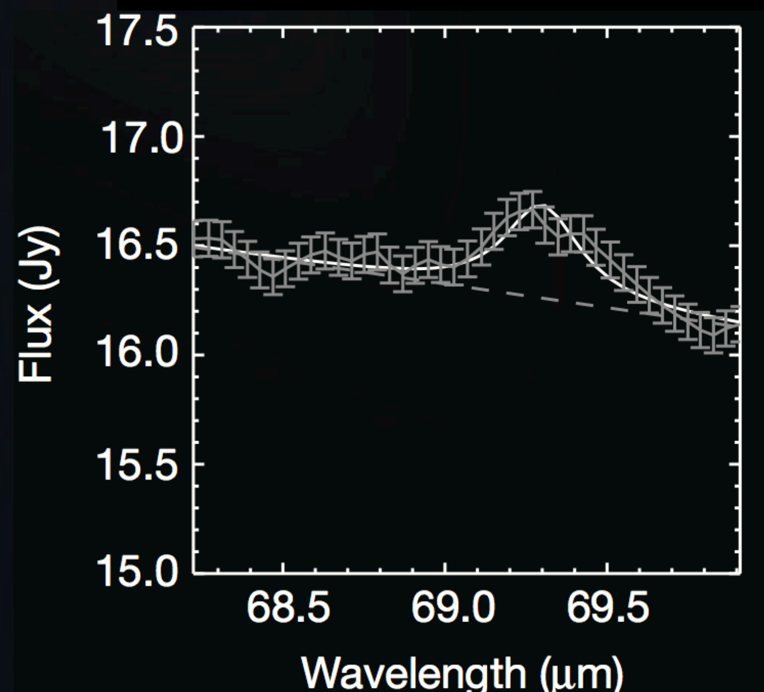
Late Heavy Bombardment



Warm, water- and carbon-rich dust in the terrestrial habitable zone -> Period of Late Heavy Bombardment (Lisse et al. 2012)

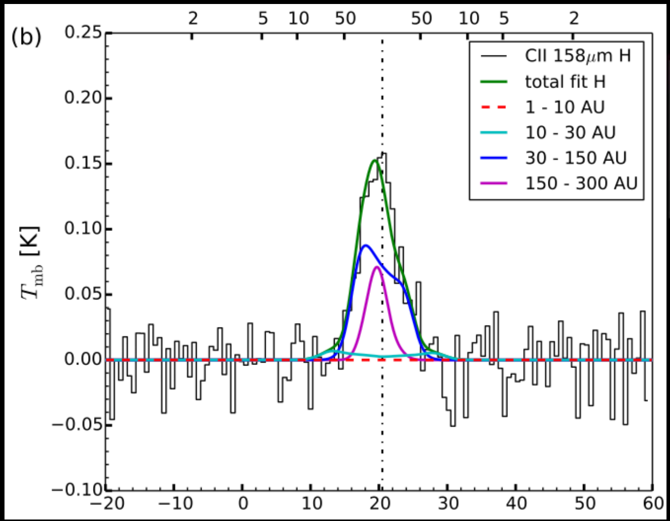
β Pictoris Silicate Mineralogy

Herschel PACS observations of the 69 μm forsterite feature indicate that the cold dust at 15 – 45 AU is Magnesium-rich (with $Mg_{2-2x}Fe_{2x}SiO_4$, x = 0.01±0.001)



De Vries et al. (2012)

β Pictoris Gas

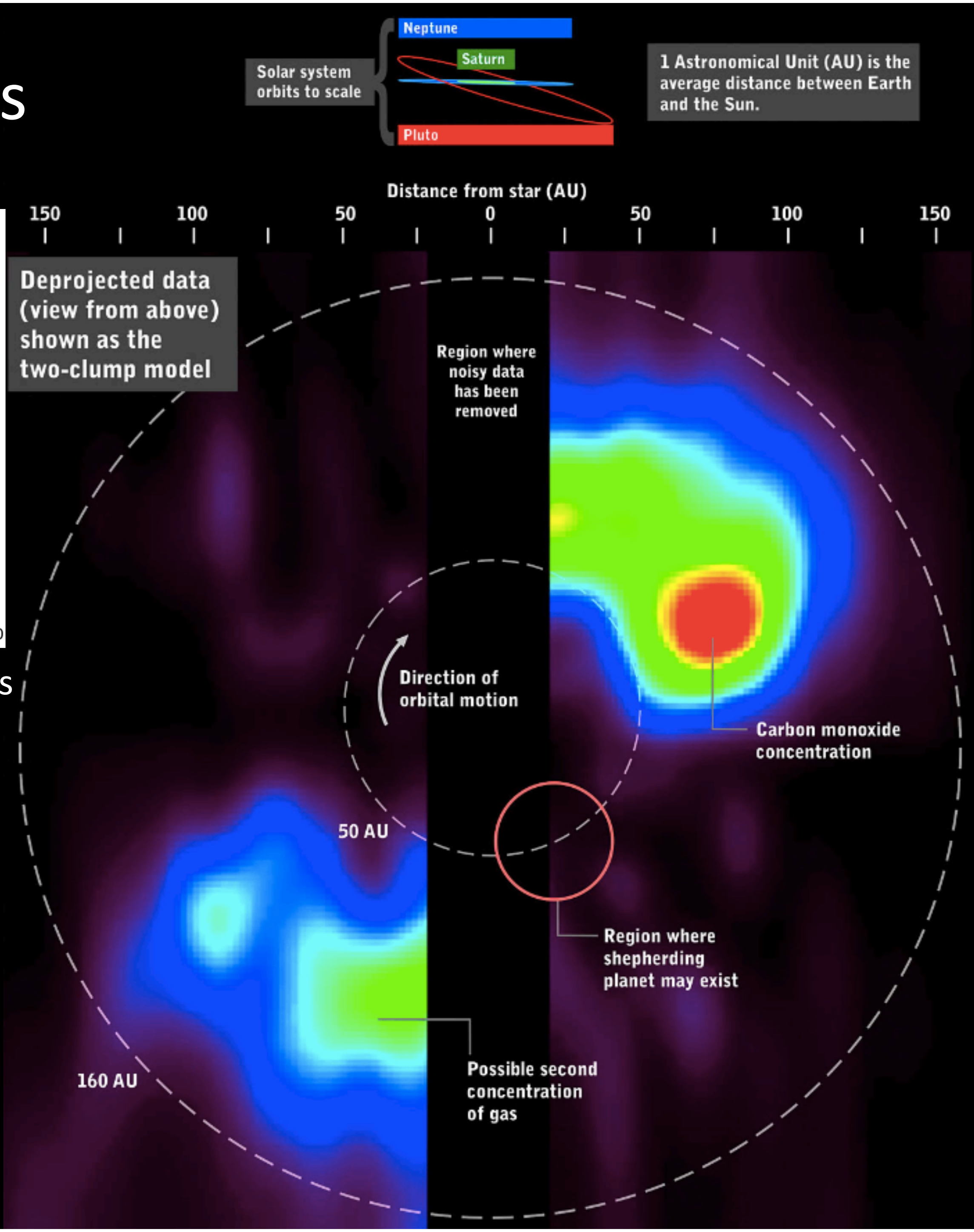


Herschel OI and C II line detections (e.g. Cataldi et al. 2014):

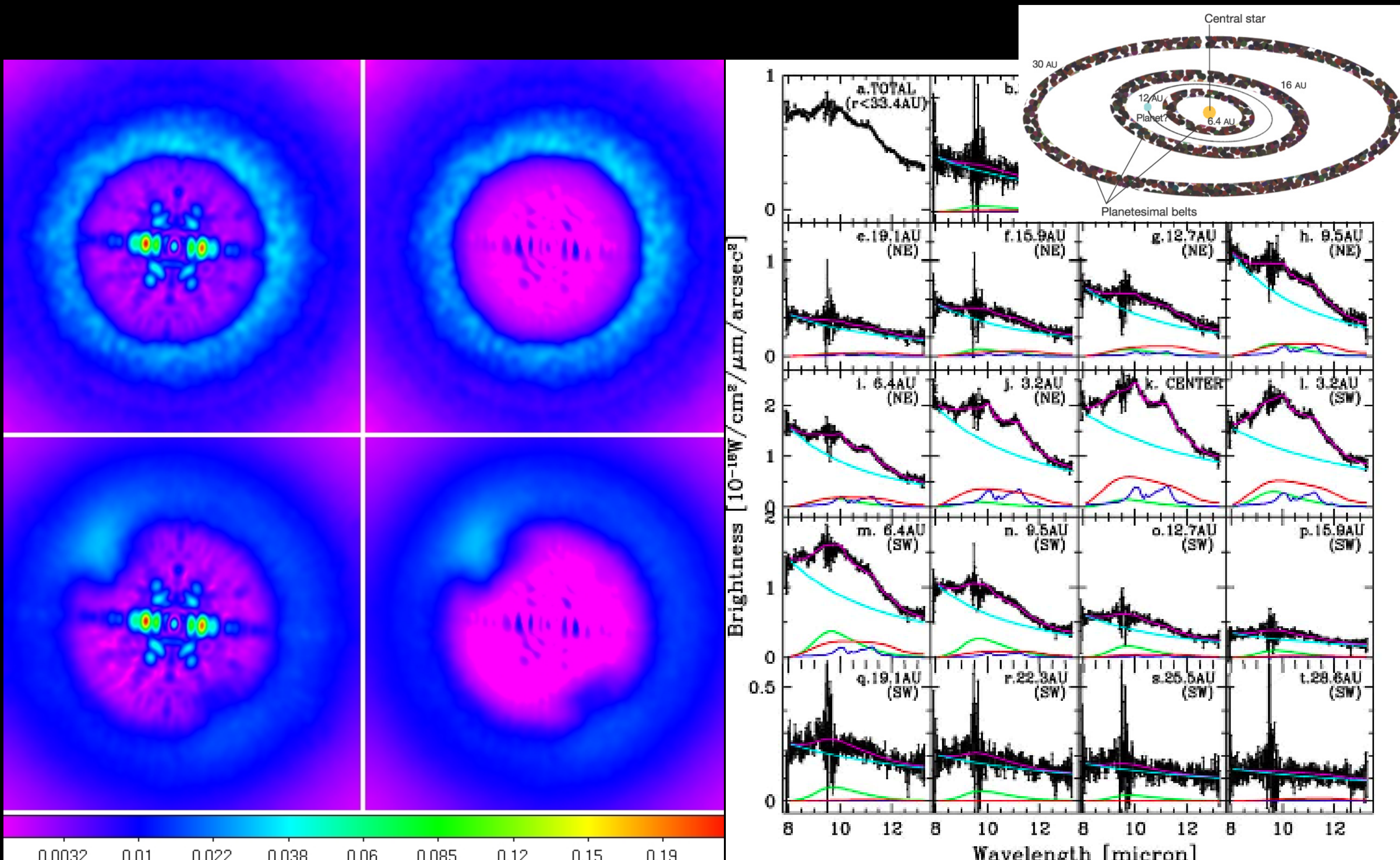
- Photo dissociation products of molecular gas

ALMA CO J=3-2 Emission map (Dent et al. 2014):

- The clump may indicate that there is an additional >10 M_{earth} planet that traps the comets in the 2:1 and 3:2 mean motion resonances

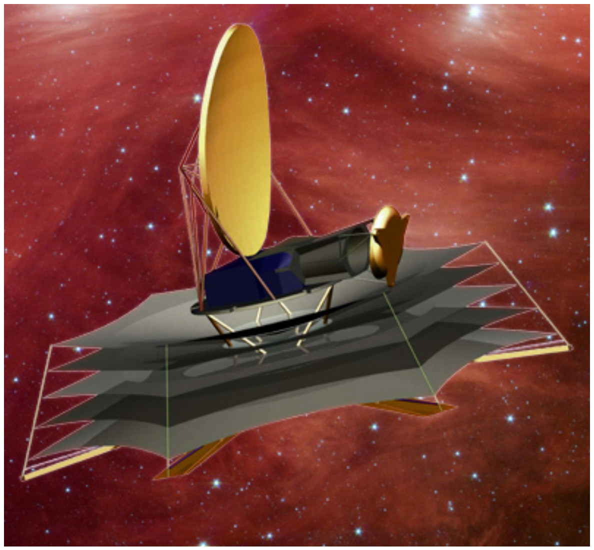
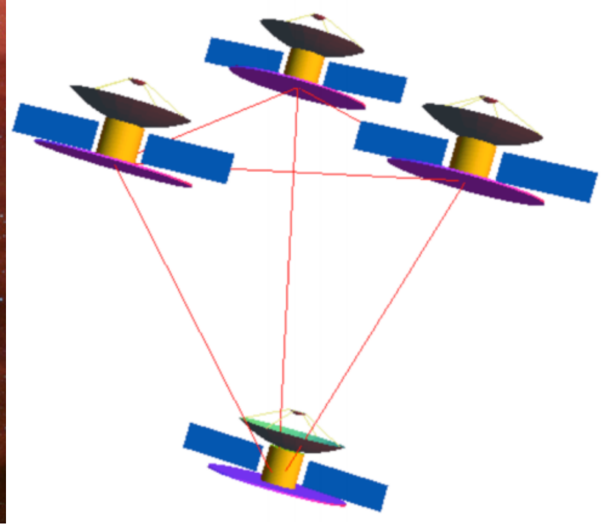
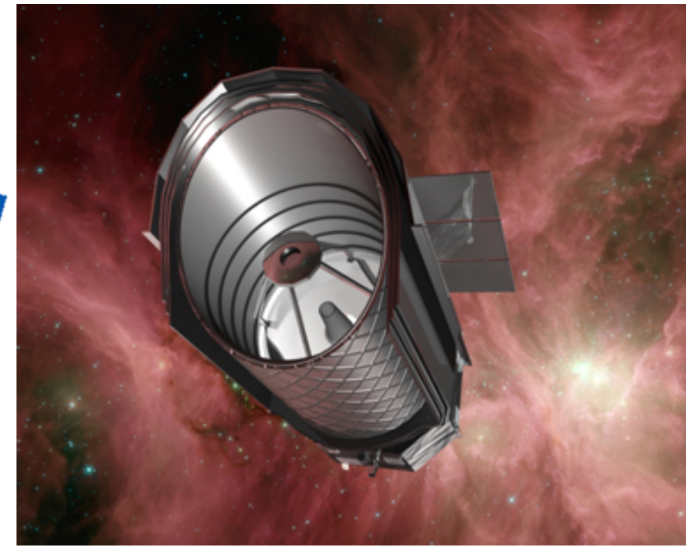


Detailed Characterization using JWST



Okamoto et al. (2005)

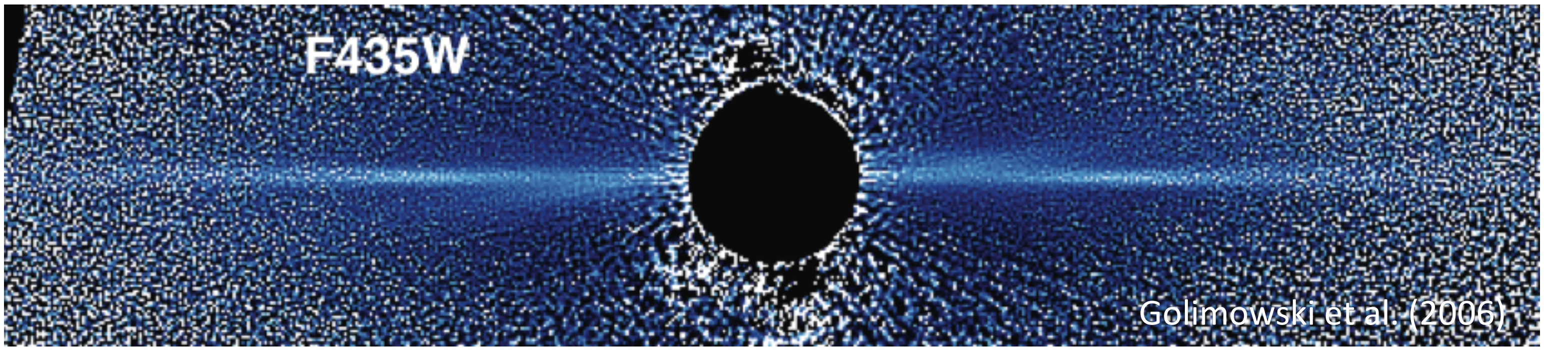
Questions to be addressed by the Next Generation of Far-Infrared Missions…

- What are the demographics of debris disks around late-type stars?
- What is the composition of the cold dust component (e.g. silicate, phyllosilicate, ice)?
- How common is atomic (e.g. O I, C II) and molecular (e.g. CO, SiO) gas in debris disks?

M-type Star Continuum Estimates

AU Mic is an ~10 Myr old M1Ve star with a fractional infrared luminosity $L_{IR}/L_* = 4.3\times10^{-4}$ located at a distance ~10 pc (Plavchan et al. 2009)

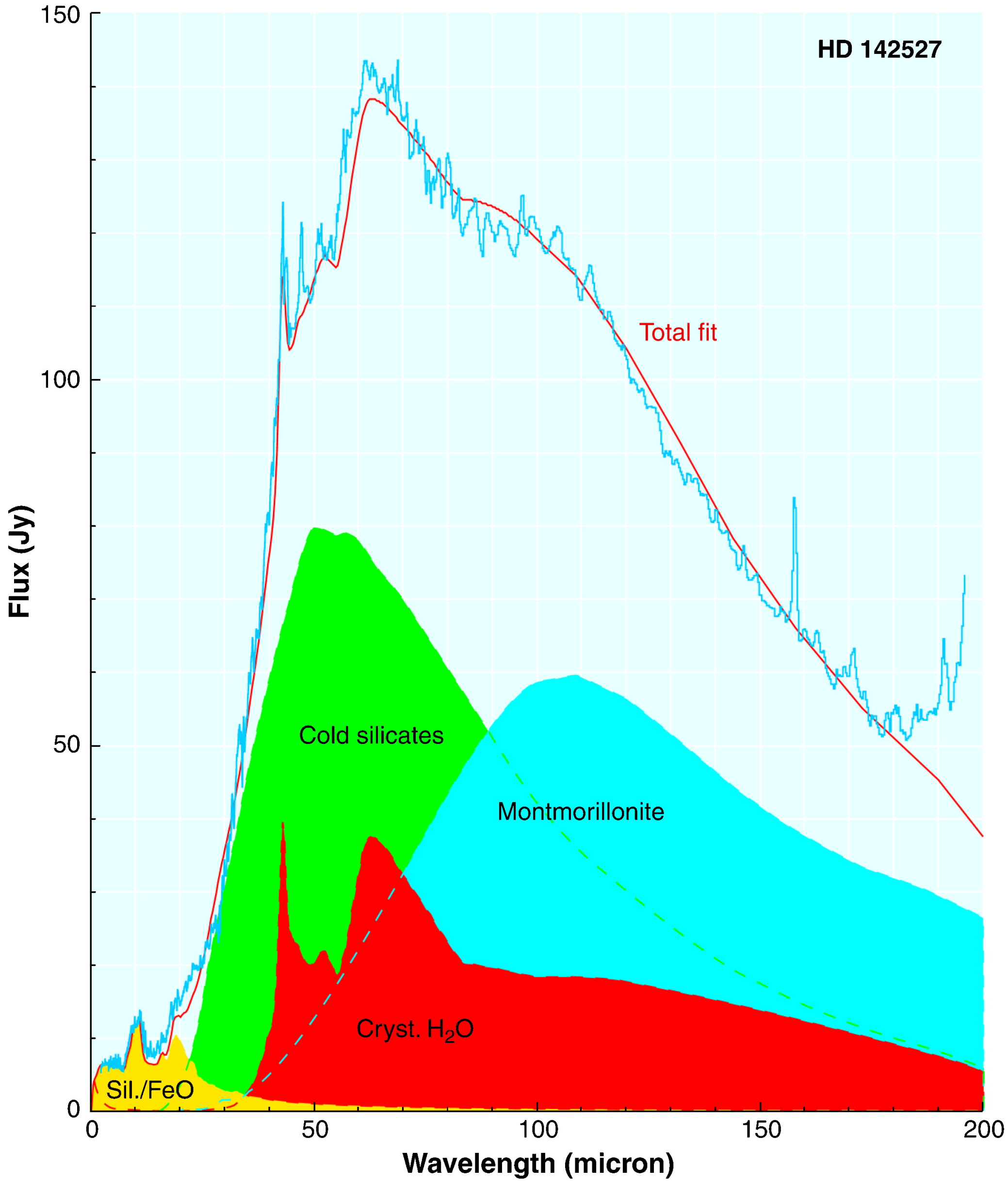


Scaled AU Mic 70 µm Fluxes

	10^{-3}	10^{-4}	10^{-5}
10 pc	565 mJy	56.5 mJy	5.7 mJy
50 pc	22.6 mJy	2.3 mJy	0.2 mJy
250 pc	0.9 mJy	0.09 mJy	0.009 mJy

Far-infrared surveys with a sensitivity of ~10 µJy could definitively measure the demographics of debris dust around all main sequence stars.

Water Ice and Phyllosilicates

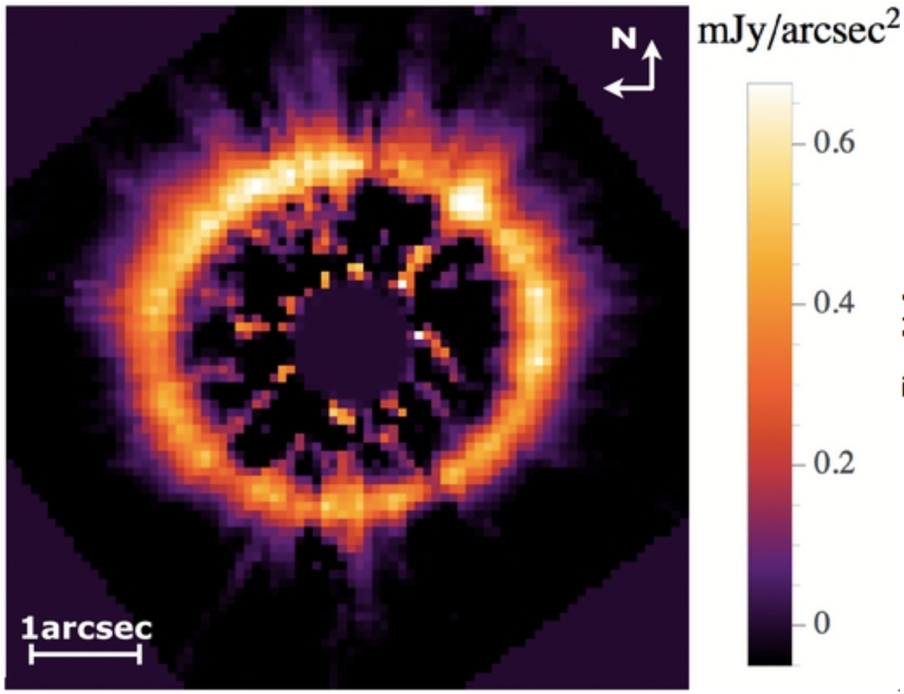


- ISO far-infrared spectroscopy of a pre-main sequence star
- Warm dust component (500-1500 K), dominated by silicate emission with some C-rich dust (Graphite and [CII])
- Cool dust component (30 - 60 K), dominated by O-rich dust. Crystalline water ice and hydrous silicates are present in the cold environment

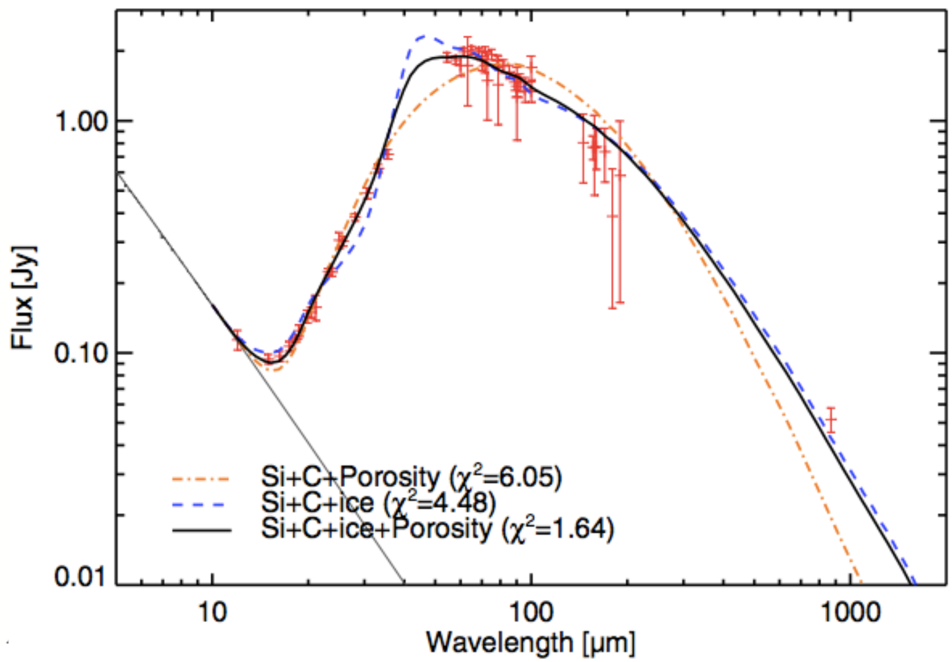
(Malfait et al. 1999)

Water Ice Detection Challenges

Multi-wavelength modeling of the disk around the Pic Moving Group member, HD 181327, suggests that the dust in this system is water-ice rich (Lebreton et al. 2012, Chen et al 2008)



NICMOS 1.6 µm image (Soummer et al. 2014)

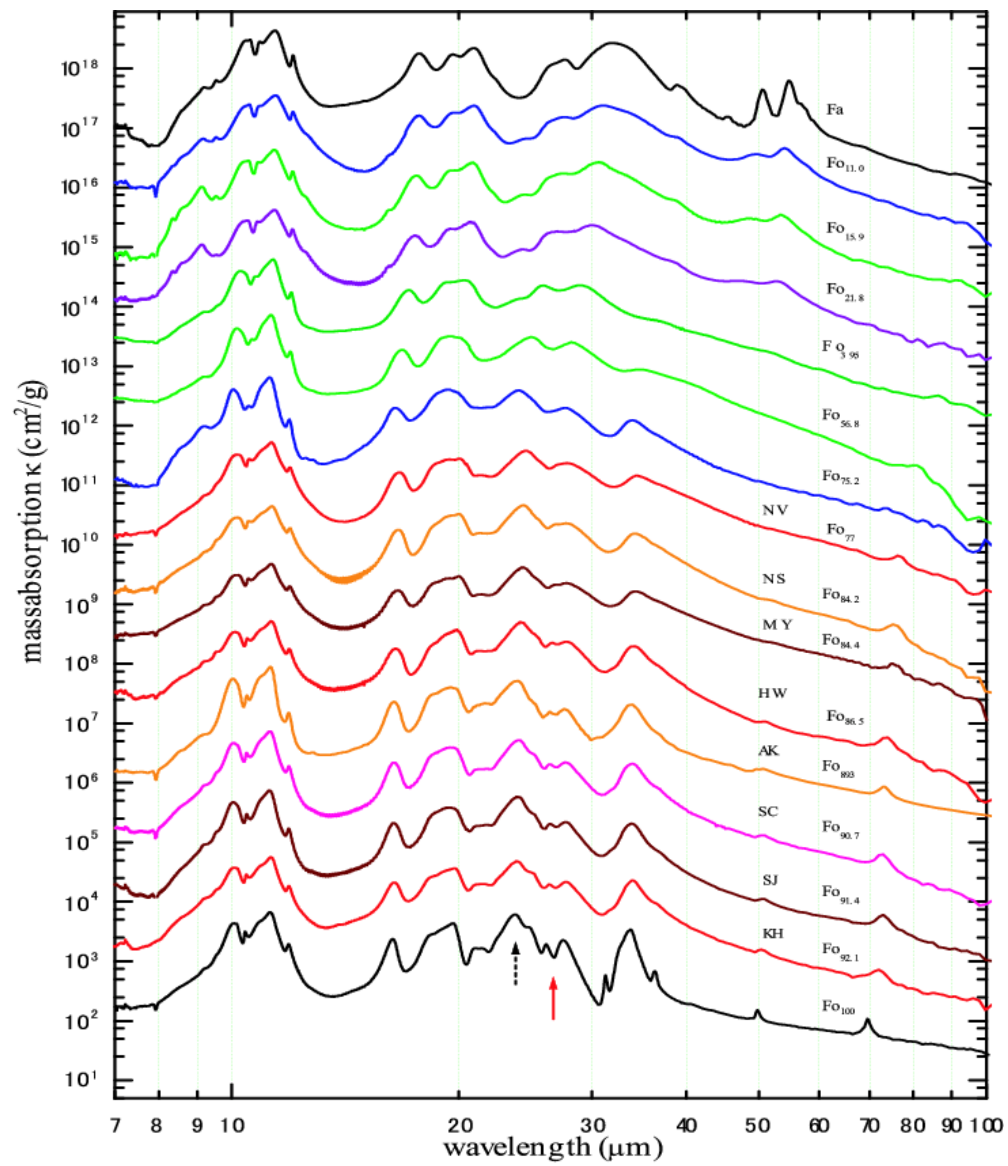


Spitzer and Herschel SED (Lebreton et al. 2012)

Since there are no strong crystalline features, it is particularly important to accurately correct the Spectral Response Function over a very large wavelength range.

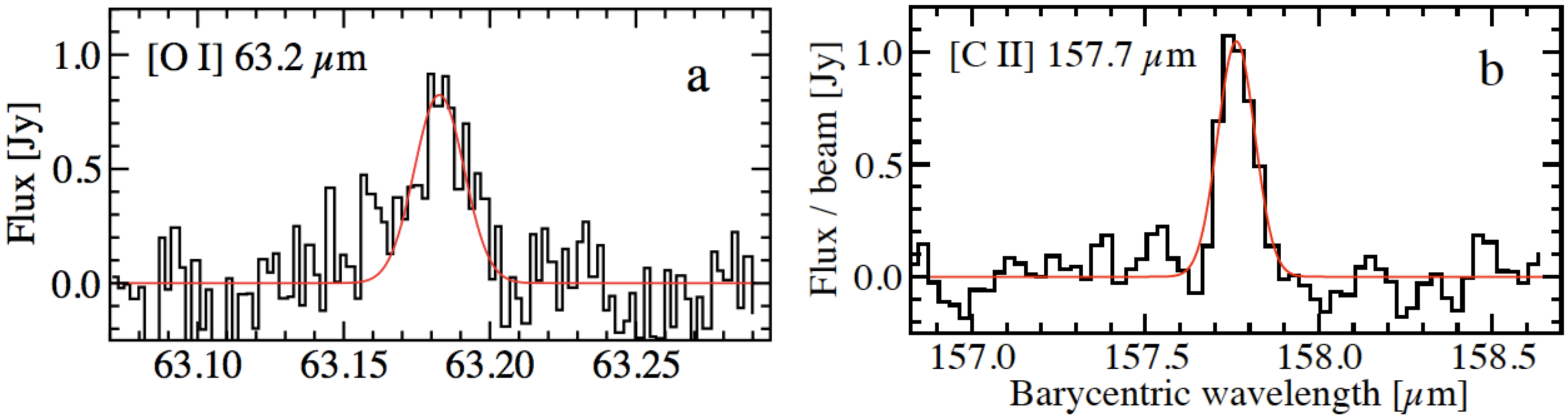
Characterizing Cold Silicate Dust

- Requires spectral resolution ($R \geq 1000$)
- Mg:Fe ratio is inferred from peak position
- Grain crystallization and size are inferred from the shape of the emission features
- If dust is co-spatial, then grain temperature is inferred from relative intensities of emission features



(Koike et al. 2003)

Atomic Line Flux Estimates

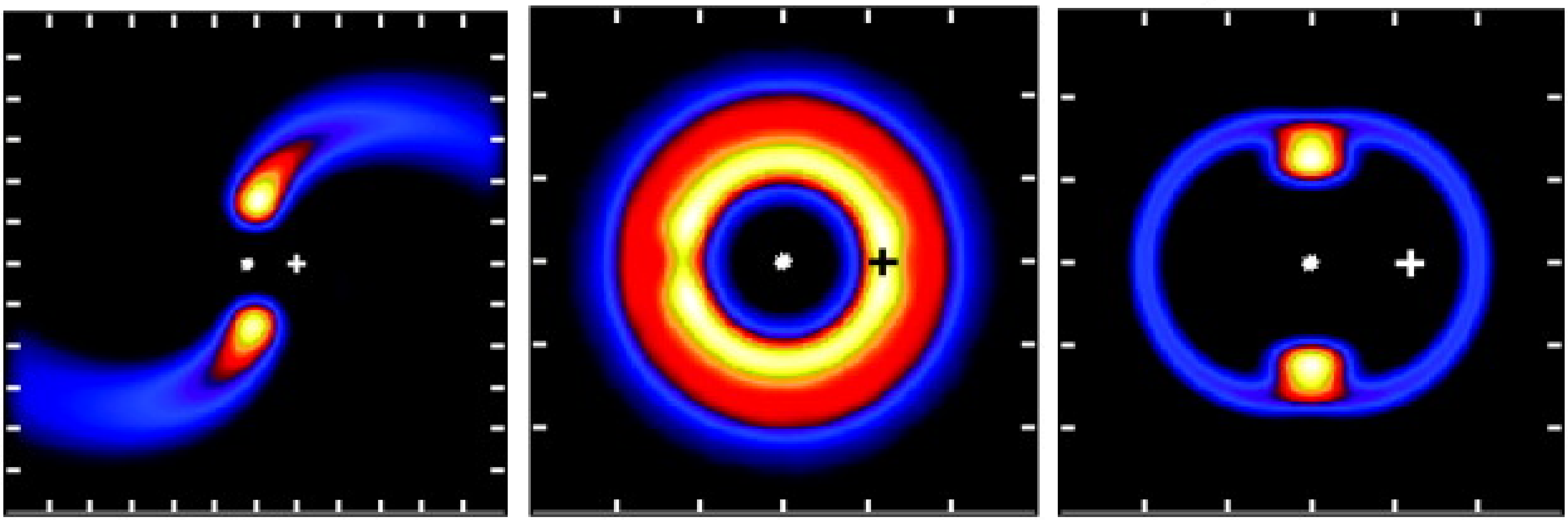


Star	Age (Myr)	F_ν(70 μm) (mJy)	F([C II]) (W m^{-2})	References
β Pic (above)	20	13000	3.4×10^{-17}	Brandeker et al. 2014
49 Cet	40	2100	3.7×10^{-18}	Roberge et al. 2013
HD 32297	30	1000	2.7×10^{-18}	Donaldson et al. 2013
η Tel	20	7.8	2.3×10^{-18}	Riviere-Marichalar et al. 2014

If gas mass is proportional to cold dust mass, then young debris disks may possess C II line fluxes of at least as small as 7.7×10^{-20} W m^{-2} (assuming 70 μm fluxes of 30 mJy).

Grain Dynamics Revealed via Multi-wavelength Thermal Emission Mapping

$\beta = 10$ | $\beta = 0.01$ | $\beta < 0.001$



Micron-sized grains
Spitzer/JWST

~100 μm grains
Far-IR Interferometry

> ~1 mm grains
ALMA

(Wyatt 2006)

Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	30 - 250
Angular resolution	arcsec	~0.1”
Spectral resolution, ($\lambda/\Delta\lambda$)	dimensionless	1000
Continuum sensitivity	μJy	At most a few
Spectral line sensitivity	10^{-19} W m^{-2}	0.1
Instantaneous FoV	arcmin	100”
Number of target fields	dimensionless	1000
Field of Regard	sr	All sky